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METHOD FOR REDUCING CRYOSTAT PRESSURE DURING A HEATER INDUCED MAGNET QUENCH

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Introduction:

This report examines the possibility of employing surge chambers connected through open lines to the single-phase helium system of the energy doubler. During a quench, fluid from the single-phase space of the magnets will be forced into the surge chamber. The temperature of the surge chamber needs to be low enough to present essentially zero cooldown duty, but high enough to contain essentially zero helium inventory. In that case, the surge vessel can be cooled to 4-8°K very quickly and will at that temperature level contain a large amount of helium.

It appears that a temperature level of 20-25°K is about right. Enthalpy of the metal walls of the surge vessel (stainless steel) is then of the order of .032 to .061 joules per gram, while gaseous inventory is of the order of 4.4 to 3.5 grams per liter of volume (at 1.8 ata). In order for the system of magnets and surge vessels to operate satisfactorily over long periods of time, flow between surge vessel and magnets needs to be zero or, at most, be limited to small amounts per excursion. Otherwise, there will be transport of large amounts of heat from the 20-25°K to the 4.5°K level. The methods by which flow between surge vessel and magnets may be controlled are discussed.

Summary:

1. It is feasible to equip the energy doubler with surge vessels and achieve a large reduction in the pressure generated during a quench.

2. The surge vessel needs to be maintained at a temperature level of 20-25°K.

3. Flow between magnet and surge vessel during normal energy doubler operation needs to be essentially zero to prevent transport of large amounts of heat from surge vessel to magnets.

4. A "regenerator" with a capability of storing a few hundred joules of heat could be employed between surge vessel and magnets to reduce effect of flow in and out of surge vessel during normal magnet operation.

5. Heat leak from the surge vessel is removed by a small bleed of helium from the surge vessel.

Recommendation:

Equip a four dipole magnet system at B-12 with surge chambers, and evaluate performance for steady state operation and under induced quenches up to i = 4,000 A.

1. Arrangement of Equipment:

Figure 1 shows the schematic arrangement of the single-phase fluid system of the magnets and connection to the surge vessel. The tube connecting surge vessel and magnets is surrounded by a jacket over its full length. This jacket contains helium under some pressure. This pressure serves as an indicator and possibly controller to determine what the temperature gradient in the connecting tube is.

The surge vessel is insulated by a layer of superinsulation. The heat leak into the surge vessel is removed from time to time by bleeding a small amount of vapor from the vessel through the relief valve. The signal for this action is provided by the pressure sensor in the jacket surrounding the connecting tube between surge vessel and magnet. If we assume a heat leak of .5 W (roughly .1 W/ft^2) for the surge vessel, average flow of gas out of the surge vessel needs to be .00385 g/sec (equivalent to .11 liters of liquid per hour).

2. Control of Flow between Surge Vessel and Magnets:

2.1 As soon as pressure in the magnet cryostat exceeds that of the surge vessel, flow will start. Table I shows the effect of adding small quantities of liquid helium to the surge vessel. The data of Table I are based on the following:

a) Surge vessel volume is 22.6 liters.

b) Initial temperature and pressure are 21°K and 1.8 ata, respectively.

c) Complete mixing occurs in the surge vessel.

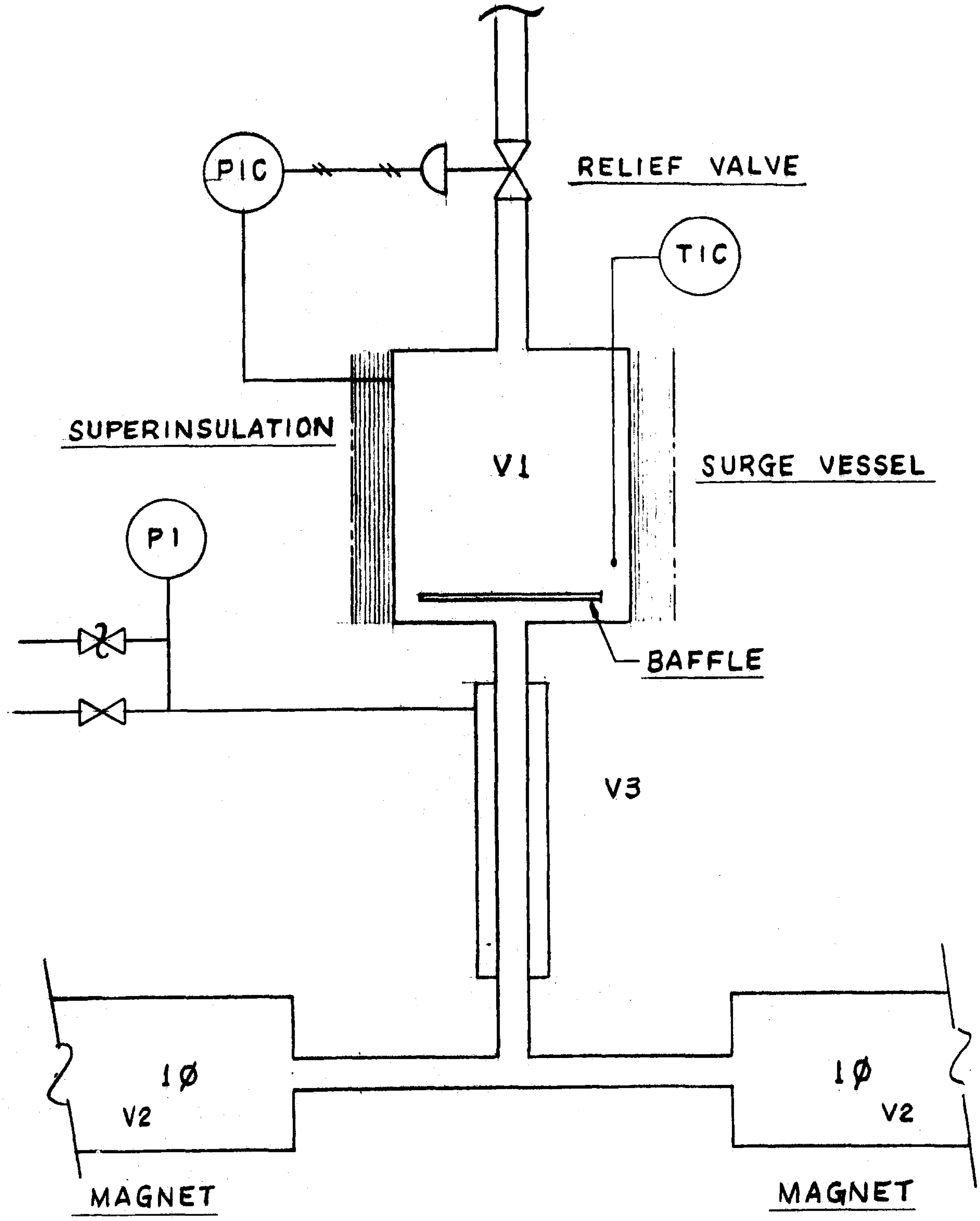

FIGURE 1

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TABLE I

Liquid Transferred (gr):	0	10	20	30
Mass in Surge Vessel (gr):	94.78	104.78	114.78	124.78
Enthalpy of Mixture (J/gr):	122.8	112.3	103.6	96.35
Spec. Vol. of Mixture (cc/gr):	238.9	216.1	197.3	181.5
Pressure (ata):	1.8	1.8	1.8	1.8
Temperature (°K):	21.0	19.0	17.4	16.0

The large effect is temperature change. Pressure changes very little. This means that the surge volume can take up a lot of mass when magnet system pressure rises slightly. For steady state operation, it is necessary to prevent the large mass addition from happening without a change in pressure. In order to accomplish this, the initial mass transferred should be heated before entering the surge volume.

Consider a 2% upward excursion in the pressure level of 1.8 atm (.53 psig). This is roughly equivalent to adding 2 grams of mass to the surge vessel at a temperature of 21°K. The enthalpy increase of this gas when starting as liquid in the magnet is then of the order of 110 J/gr. Total heat input required is 220 joules. This needs to be available as stored heat, preferably in reversible form. Helium in a separate volume will fit the requirement.

Cooling approximately 2 grams of helium gas from 21° to 4.5 - 5°K will accomplish the task. The arrangement of Figure 1 shows a volume V3. This volume is a closed volume and contains 2 grams of helium gas. Assume a pressure of 10 ata and a temperature of 21°K. When liquid helium flows into the connecting tube between magnet and surge vessel, the pressure in volume V3 will drop, and heat transfer takes place. A temperature wave moves through the tube in the direction of the surge vessel. When all of volume V3 is cold, pressure will have decayed to a low value of 1.5 to 2 ata, then the fluid about to enter the surge vessel is approximately 4-5°K. During the process, the pressure in the surge vessel has increased by .5 psig. When the pressure in the magnets is reduced, flow proceeds from the surge vessel to the magnets, and pressure in volume V3 increases.

2.2 An alternative method may be used to add liquid to the surge vessel, as follows:

a) Keep the gas present in the surge vessel and liquid entering thermally separate to the greatest degree possible.

b) To take up large amounts of fluid from the magnets, vent gas contents of the surge vessel during the early stage of a quench.

To accomplish the above, stratification in the surge vessel needs to be maintained during normal magnet operation for all non-quench induced pressure fluctuations. This can be achieved by filling the surge vessel with a sponge-like material and providing a relatively large L/D ratio. The vessel is mounted vertically.

Table II indicates what happens to the gas in the surge vessel when its volume is reduced through in-flow of liquid:

TABLE II

Mass in Surge Vessel (gr):	94.78	250	401	810
Pressure (ata):	1.8	2.0	2.2	3.0
Temp. of Gas (°K):	21	22	22.8	25.8
Spec. Vol. Gas (cc/gr)	238.9	225.4	212.4	177.0
Liquid Transferred (liters):	0	1.27	2.51	5.86

In order to make the stratified surge vessel work, it is necessary to provide excellent thermal conductivity over most of the surge vessel, with a small section (approximately 5%) maintaining stratification between 5 and 20°K. This small section may be the connecting tube between surge vessel and magnet system. Figure 2 shows a potential arrangement.

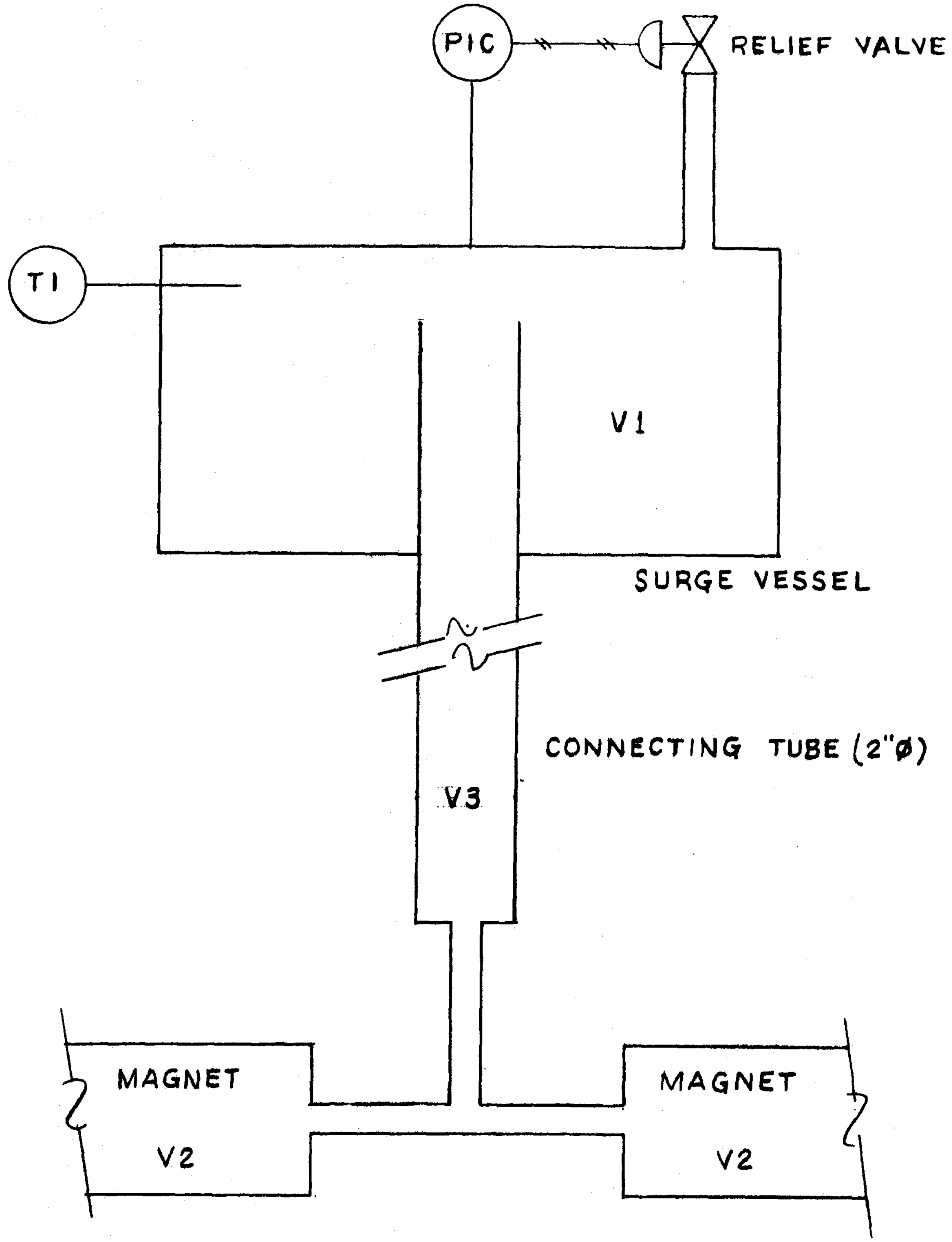

FIGURE 2

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3. Fast Removal of Liquid from the Magnets:

Rate of pressure rise in the overall system will be evaluated in several ways, as follows:

3.1 Fluid flowing from the magnets will always be at an enthalpy of 14.0 joules/gram. This implies not much heating from the quench process, at least of the fluid escaping from the magnet. The fluid mixes in the surge chamber, and the pressure relief valve only opens after a preset pressure in the surge vessel has been reached. This pressure may be selected on the basis of maximum desired pressure in the magnet cryostat.

Table III indicates the pressure, mass, temperature, and liquid helium present in the surge chamber as a function of mass transferred:

TABLE III

Mass Transferred in Grams	Mass in Surge Vessel Grams	Temp. °K	Pres. ata	Liquid Grams
-0-	94.78	21.0	1.8	-0-
125	219.78	9.5	1.8	-0-
250	344.78	6.7	1.8	-0-
375	469.78	5.4	1.7	-0-
500	594.78	4.9	1.68	-0-
625	719.78	4.85	1.72	20
750	844.78	4.87	1.75	120
875	969.78	4.91	1.8	289
1000	1094.78	4.94	1.85	400
1125	1219.78	5.05	2.0	483
1250	1344.78	5.09	2.06	620
1375	1469.78	5.11	2.1	785

The assumption of a constant enthalpy of 14.0 J/gr of the fluid flowing from the magnet is not realistic. It is more likely that the enthalpy will rise with time and that the fluid venting from the magnet will at least be two-phase. This implies that at a pressure level of 2.1 ata, the minimum enthalpy is 17.02 J/gr.

3.2 Consider the case where the fluid enthalpy entering the surge vessel rises proportionally with the amount entered from 12.0 to 21 joules/gram for 0-10 liters vented. Table IV provides the data. Obviously, the surge chamber still will function quite well.

TABLE IV

Mass Transferred in Grams	Mass in Surge Vessel Grams	Temp. °K	Pres. ata	Liquid Grams
-0-	94.78	21.0	1.8	-0-
125	219.78	9.33	1.8	-0-
250	344.78	6.45	1.68	-0-
375	469.78	5.38	1.65	-0-
500	594.78	4.95	1.65	-0-
625	719.78	4.90	1.78	-0-
750	844.78	4.89	1.78	130
875	969.78	5.0	1.92	170
1000	1094.78	5.047	2.0	244
1125	1219.78			
1250	1344.78			
1375	1469.78			

3.3 To be able to take up more fluid, one could consider venting the original charge in the surge chamber, when liquid from the magnet is flowing in. We will assume that there is no mixing.

If the pressure in the surge vessel is kept constant, mass flow rate out of the surge vessel needs to be

$$\frac{8.5}{238.9} \times 125 = 4.45 \text{ gr}$$

for each liter of liquid added to the surge vessel. This reduction in flow rate is important in three respects, as follows:

a) Cold gas flows into a warm vent line. There is no instant vaporization of liquid accompanied by large volume expansion.

b) Mass flow rate out of the vent line is approximately 28 times smaller.

c) Sonic velocity is considerably higher at higher temperatures.

The pressure in the surge vessel will now be a function of relative flow rates in and out. Assume that on first approximation the pressure remains constant. In order to flow into the surge vessel at 10,000 cc/sec, flow out needs to be 44.5 g/sec. We will calculate some pressure drops.

a) Vent Line from Surge Vessel to Collection Header:

Mass flow rate is 353 lb/hr (44.5 g/sec). Temperature is 21°K. Pressure is 1.5 ata (average). Try a 3/4 in. OD, .035 in. wall tube. Then:

d_h = .68 in. = .0567 ft

A = .363 sq in. = .00252 ft^2

G = 140,025 lb/hr ft^2

μ = .0090 lb/ft hr

Re = 882,000

$$f = \frac{.046}{Re^{.2}} = .00298$$

ρ = .22 lb/cft

$$\frac{\Delta P}{L} = \frac{.00298 \times (38.89)^2}{193 \times .22 \times .68} = .156 \text{ psig/ft}$$

There will be heat transfer in the vent line. The heat transfer coefficient will be calculated from:

$$h = \frac{j\ C_p\ G}{Pr^{2/3}}$$

$j = .00149$

$C_p = 1.26$ Btu/lb °F

$Pr = .70$

$Pr^{2/3} = .79$

$$h = \frac{.00149 \times 1.26 \times 140025}{.79} = 333$$

For a wall at constant temperature:

$$\ln K = \frac{h\ A}{C_p W}$$

Where: $K = \dfrac{T_{wall} - T_{in}}{T_{wall} - T_{out}}$

A = surface area (5 ft of tube)

W = flow rate

We find:

$$\ln K = \frac{333 \quad \times .89}{1.26 \times 353} = .666$$

$K = 1.95$

The gas warms to 157°K, when all of the vent line is warm. The vent line will cool rapidly since the gas takes up: 44.5 x (157 - 21) x 5.2 = 31,470 W. Mass of the vent line is 1.37 lb. To cool to 80°K requires removal of 47,900 joules of heat. Apparently, it will require more than one second to cool the vent line. Pressure drop of the gas flowing through the pipe during the first second needs to be based on a much higher temperature than 21°K. Assume 150°K. Then:

μ = .03

Re = 264,647

f = .0038

ρ = .032 lb/cft

$$\frac{\Delta P}{L} = \frac{.0038 \times (38.89)^2}{193 \times .032 \times .68} = 1.35 \text{ psig/ft}$$

The vent line is just barely large enough to handle the desired flow rate during the first second of the venting cycle.

b) Liquid Line from Magnets to Surge Vessel:

The desired flow rate is 10 liters per second or 9,912 lb/hr. In order to accommodate the flow rate with a reasonably low pressure drop and low velocity heads, a connection of 1 in. diameter (.035 in. wall) will be used. Then:

Flow Area = .0047 ft^2

d_h = .93 in. = .078 ft

$$G = \frac{9912}{.0047} = 2.1 \times 10^6 \text{ lb/hr ft}^2$$

μ = .0065 lb/ft hr

Re = 25×10^6

$$f = \frac{.046}{Re^{.2}} = .0015$$

ρ = 6.6 - 7.5 lb/cft

$$\frac{\Delta P}{L} = \frac{.0015 \times (583)^2}{193 \times .93 \times 6.6} = .43 \text{ psig/ft}$$

The velocity of the liquid flowing through the line is:

$$\frac{2.1 \times 10^6}{6.6 \times 3600} = 88.4 \text{ ft/sec}$$

A velocity head is then:

$\Delta P = 1/2\ \rho v^2 = 5.6$ psig

It appears that the most important consideration for the design of the line connecting surge vessel and magnets is the value of the velocity head required to accelerate the liquid into the surge vessel. It is also obvious that it may be difficult to prevent mixing of the liquid entering the surge vessel with the gas present.

4. Pressure Drop in Vent Line of Dipole with Conventional Vent System:

Figure 3 shows the pressure versus time in the energy doubler magnets after a heater induced quench has been initiated. It appears that qualitatively the large pressure spike for a short period of time can be explained by examining the behavior of the vent line during the initial second of flow.

Consider the case of a vent line with 5 cm^2 cross section for flow and a warm length of 2 ft. If the line has a wall thickness of .035 in., warm mass will be of the order of 360 grams of stainless steel. At time zero the line pressure is 1.8 ata, and the warm section contains .09 grams of helium gas. This gas will be vented in a matter of milliseconds. At that time, liquid helium is accelerated into the vent line to a high velocity. The rate of acceleration of the first 10-15 grams of liquid helium is very high, because:

a) Force on this slug of helium is of the order of $.5\ Kg/cm^2 \times 5 = 2.5$ Kg.

b) Mass of liquid = 12.5 g.

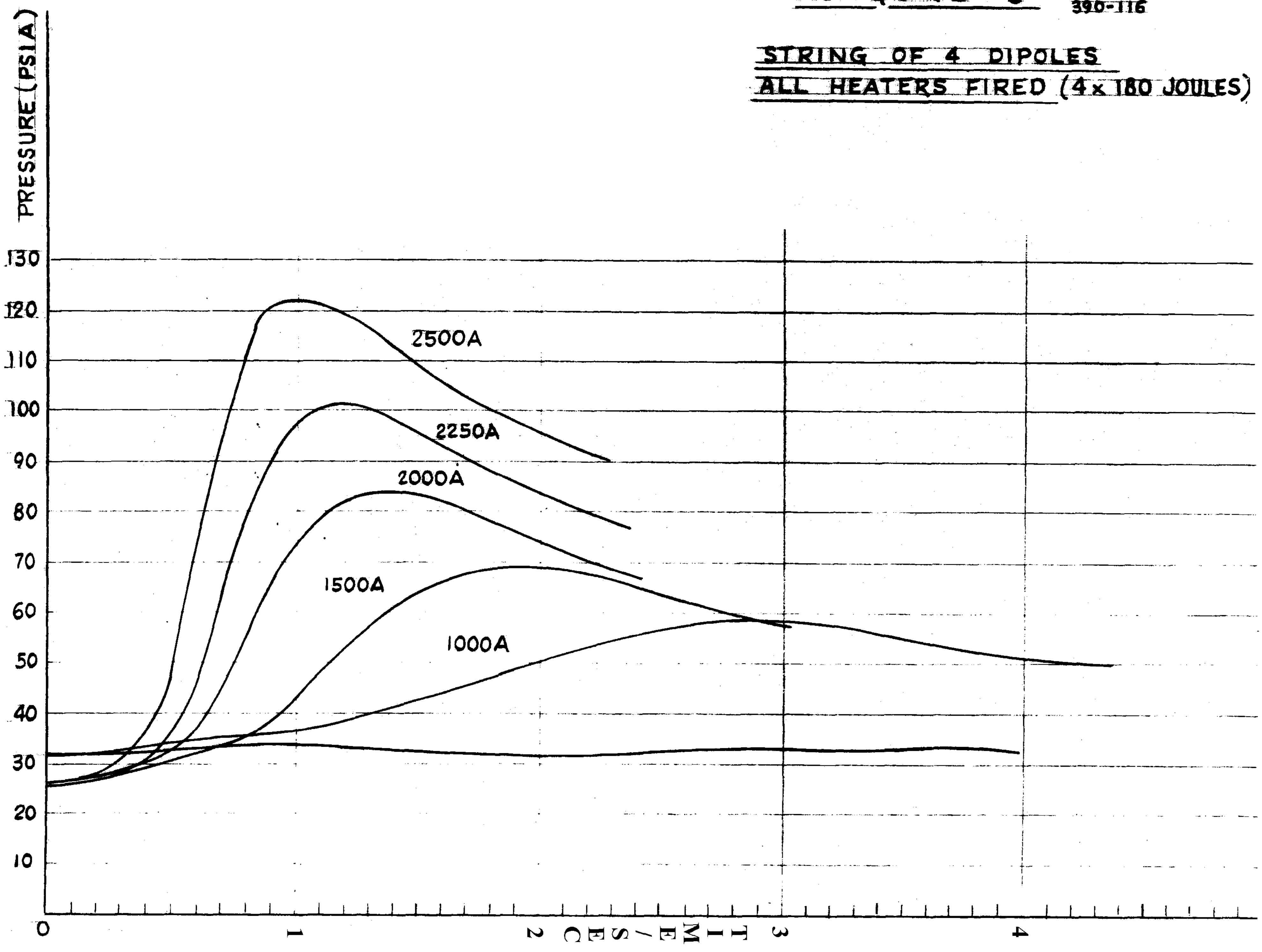
c) $a = 200$ g's.

Velocity attained by this liquid in traveling 2 ft is of the order of 4,800 cm/sec (ignoring friction developed in the line). Time to cover the 2 ft length is of the order of 25 milliseconds.

When the liquid reaches the warm pipe, heat transfer is initiated. This heat transfer serves to increase the volume of the mass. If the volume increase cannot be accommodated, pressure will rise locally. An estimate of the rate of heat transfer can be made by calculating

FIGURE 3 390-116

STRING OF 4 DIPOLES
ALL HEATERS FIRED (4 x 180 JOULES)



coefficient and temperature rise of the fluid in traveling through the pipe. Assume a liquid velocity of 30 m/sec. Then:

$$\dot{M} = 1875 \times \frac{3600}{454} = 15{,}000 \text{ lb/hr}$$

$$G = \frac{15000}{5} \times 930 = 2.79 \times 10^6 \text{ lb/hr ft}^2$$

$$\mu = .0065$$

$$Re = 35.77 \times 10^6$$

$$f = \frac{.046}{Re^{.2}} = .0014$$

$$j = \frac{.023}{Re^{.2}} = .0007$$

$$C_p = 2.4 \text{ Btu/lb °F}$$

$$Pr = 1.8$$

$$Pr^{2/3} = 1.48$$

$$\rho = 6.6$$

$$h = \frac{j\ C_p\ G}{Pr^{2/3}} = \frac{.0007 \times 2.4 \times 2.79 \times 10^6}{1.48}$$

$$= 3{,}167 \text{ Btu/hr ft}^2 \text{ °F}$$

$$\frac{\Delta P}{L} = \frac{.0014 \times (775)^2}{193 \times 6.6 \times 1} = .66 \text{ psig/ft}$$

Amount of heat transferred in .02 seconds from ambient temperature pipe of .5 ft^2 surface area is then 5,060 joules. If this heat is taken up by 12 grams of helium, enthalpy rise will be of the order of 420 joules/gram, and temperature rise will be to 80°K. In order to maintain constant pressure, the fluid velocity needs to be increased by a factor of 100. We will exceed sonic velocity by a wide margin and, consequently, pressure will rise. The pressure in the vent line would rise above that of the magnet vessel and, as a consequence, flow will slow down and possibly reverse. If the flow were to reverse, some heat is transported back into the liquid of the magnet reservoir. The amplitude of the potential pressure oscillations in the vent pipe during the cooldown process will be small, because liquid helium is light and can be accelerated and decelerated with small forces.

The above demonstrates that the vent line has a limited flow capability during the cooldown process.

5. Heat Transfer from Dipole to Liquid Helium:

Figure 3 indicates a pressure rise from 1.8 to approximately 8 ata for a quench with i = 2,500 A. If we assume that little helium is vented during the first second, we can estimate the amount of heat added to the liquid helium in order to reach 8 atm. Consider a constant specific volume of the mass. Then conditions of the fluid at time t = 0 and t = 1 sec are as follows:

TABLE V

t	=	0	t	=	1 sec
V_s	=	8.45 cc/gr	V_s	=	8.45
P	=	1.8 ata	P	=	8 ata
T	=	4.6°K	T	=	6.25°K
H	=	12.0 J/gr	H	=	21.6 J/gr
S	=	3.810	S	=	4.606

If the fluid had been compressed without addition of heat, conditions would have been as follows:

TABLE VI

t	=	0 sec	t	=	1 sec
V_s	=	8.45 cc/gr	V_s	=	7.47
P	=	1.8 ata	P	=	8.0
T	=	4.6°K	T	=	5.36
H	=	12.0 J/gr	H	=	16.92
S	=	3.810 J/gr °K	S	=	3.810

The real picture is somewhere between conditions of Tables V and VI. Table VII indicates the heat added to part of the liquid helium inventory in order to obtain the pressure of 8 ata. It has been assumed that essentially no fluid vents during the first second after the quench has been initiated.

TABLE VII

Magnet Inventory Grams	Heated Helium Grams	Heat Added Joules	Temp. Heated He °K	Temp. Compr. He °K
1,775	100	4,458	11.3	6.25
1.775	200	5,548	8.83	6.25
1,775	300	5,904	8.06	6.25
1,775	400	6,360	7.65	6.25
1,775	500	6,725	7.40	6.25

The numbers of Table VII change little if we assume that some fluid has been vented during the first second after quench initiation. For example, if 100 grams of fluid had been vented during the first second, heat added to 100 grams of liquid to reach 8 ata would have been 6,000 joules.

The conclusions to be drawn from the above are the following:

a) Approximately 6,000 to 8,000 joules are transferred to the helium in the vicinity of the heated windings.

b) To lower the pressure in the magnet cryostat, fluid volume needs to be increased more rapidly.

c) Liquid removal from a dipole at a rate of 6-10 liters/sec will limit pressure in the cryostat to approximately 30 psig.

d) The vented fluid needs to be stored in a cold volume to allow vent line cooldown by a relatively small flow rate of cold helium gas.